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Scaling Study for SP-100 Reactor Technology

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INTRODUCTION

The reactor technology for the SP-100 program is intended to be applicable for power systems from tens of kilowatts to one megawatt electrical. Future power requirements may extend well into the multimegawatt electrical power range. If the reactor technology developed for the SP-100 program could also be used for higher power systems, rather than establishing a new reactor program, significant savings in development costs are possible. In this study, we explored several ways of extending SP-100 reactor technology to higher power levels. One approach was to use the reference SP-100 pin design and increase the fuel pin length and the number of fuel pins as needed to provide higher power capability. The impact on scaling of a modified and advanced SP-100 reactor technology was also explored. Finally, the effect of using alternative power conversion subsystems, with SP-100 reactor technology was investigated.

One of the principal concerns for any space-based system is mass; consequently, this study focused on estimating reactor, shield, and total system mass. The RSMASS code (Marshall 1986) was used to estimate reactor and shield mass. Simple algorithms developed at NASA Lewis Research Center were used to estimate the balance of system mass. Power ranges from 100 kWe to 10 MWe were explored assuming both one year and seven years of operation. Thermoelectric, Stirling, Rankine, and Brayton power conversion systems were investigated. The impact on safety, reliability, and other system attributes, caused by extending the technology to higher power levels, was also investigated.

POTENTIAL MODIFICATIONS AND LIMITATIONS

Two General Electric Company reports (GE May 1988; GE March 1988) describe the basic SP-100 reactor and shield subsystem. For the reference SP-100 design, the power system provides 100 kWe for a period of seven years operation. The reactor fuel is in the form of 0.77 cm OD, niobium alloy clad UN fuel pins. A liquid lithium coolant carries heat from the reactor to thermoelectric power conversion modules. Waste heat is dumped to space by means of a radiator. The radiation shield uses layers of LiH, W alloy, and Be.

When modifications and advancements relative to the reference SP-100 technology were investigated, some limitations were required. If changes are significant enough, it may be justifiably argued that the reactor is not an improved SP-100, but a new reactor subsystem. We have defined SP-100 technology to be limited to UN pin-type fuel, cooled by a liquid (non-boiling) lithium coolant. The size of the pin, the fuel/clad gap, the fuel density, cladding material, cladding thickness, plenum length, fill gas, fuel porosity, fuel manufacturing process, and cladding temperatures may be changed to assess the impact of improved SP-100 technology. The use of a different cladding material represents the most significant deviation from the reference SP-100 reactor technology.

APPROACH

A detailed mass analysis is not warranted for a study of this nature; consequently, the RSMASS code was used to estimate the reactor and shield mass. RSMASS uses approximations rather than correlations or detailed calculations to estimate the reactor fuel mass and the masses of the moderator, structure, reflector, pressure vessel, miscellaneous components, and the reactor shields. The minimum fuel mass is limited by either the neutronics of the reactor, core thermal limitations, or the damage to the fuel over the projected operational lifetime. RSMASS computes these limits individually and selects the largest as the reactor fuel mass.

Reactor masses were first calculated assuming the reference pin design. The length of the pin and the number of pins were increased, as needed, to achieve higher power levels. The reference SP-100 fuel parameters are shown in Table 1 and the reference payload dose limits are presented in Table 2. In this study the designation "near term" will be used for subsystems that could be developed within five years if a concerted effort is made and adequate funding is available. Based on this definition, the reference SP-100 reactor and shield are near-term technologies.

Since modifications and improvements relative to the reference (near term) design could reduce mass, calculations were also performed for pin geometries optimized to higher power levels and for advanced cladding. Many fuel experts were consulted to determine the possible improvements and limitations to the fuel technology. Based on these consultations, "far-term" parameters were chosen for a reactor concept that could be available by extending SP-100 reactor technology beyond the limitations of a near term technology. "Goal" parameters, which represent a probable upper limit for the technology, were also developed. The assumed far term and goal parameters are also presented in Tables 1 and 2. These reactor and shield mass calculations were carried out at Sandia National Laboratories (SNL).

System mass calculations were then performed at NASA Lewis Research Center to estimate the balance of system mass for thermoelectric, Stirling, Brayton, and Rankine power conversion. The algorithms for the balance of system mass were developed and referenced, for the appropriate components, to the SP-100 reference design as described by General Electric Company (GE May 1988). The balance of the system includes the power conversion subsystem, radiators, heat exchangers, structure, and power conditioning. (The power conditioning masses are not included in this paper, however, since power conditioning mass depends significantly on the payload requirements, which have not be defined.) The Stirling power conversion system model was based on studies done at NASA Lewis Research Center. The Rankine power conversion system performance model was based on ORNL's ALKACYCL code (Moyers 1985), while the component masses were based on the results published by SPI (Wetch 1988). The Brayton subsystem performance and mass estimates were calculated using in-house NASA Lewis models. The parameters assumed for the balance of the system for near term, far term, and goal are presented in Table 3. These calculations were carried out for several coolant temperatures assuming both one and seven years of operation.

CALCULATIONAL RESULTS

The reactor mass is plotted as a function of thermal power level in Figure 1 for near-term, far-term, and goal technology assuming seven years of operation. As can be seen, our reactor mass estimates are in excellent agreement with the GE prediction. Our shield mass estimates also showed excellent agreement with GE predictions. The far-term SP-100 reactor and shield mass estimates are comparable to the predicted masses for a number of proposed multimegawatt liquid metal cooled reactor concepts (Marshall 1986). Near-term reactor mass is about 30% greater than the far-term reactor mass.

The overall system mass (excluding power conditioning) is plotted as a function of electrical power for far-term power systems in Figure 2. Seven years of operation and a 1500 K maximum cladding temperature are assumed in the calculations for Figure 2 for Rankine, Stirling, Brayton, and thermoelectric power systems. In the past we have made similar calculations for power system concepts proposed specifically for multimegawatt applications (e.g., Marshall 1989). Although the ground rules and assumptions for these similar calculations were different from those used in this study, the system masses at megawatt levels for the Rankine and Stirling systems presented in Figure 2 are comparable to the masses we estimated for the proposed multimegawatt concepts (2.5-7 kg/kW). Since we could not identify any essential differences between a reactor derived from SP-100 technology and a liquid metal cooled pin-type reactor specifically designed for multimegawatt operation, comparable reactor and system masses are to be expected.

The results in Figure 2 suggest that Rankine power conversion would offer the greatest mass savings in the multimegawatt range. Although the system models have not been benchmarked against detailed calculations for all power systems, an uncertainty analysis for similar calculations, performed at SNL, confirms the basic trends shown in Figure 2. It must be pointed out, however, that we do not consider the Rankine power system to be a near-term technology, since issues such as two-phase fluid behavior in a microgravity environment may not be resolved in the near term. Futhermore, since the object of this study was only to determine the potential for scaling <u>reactor</u> technology, we did not address the issues of system reliability, safety, etc. These results, consequently, should not be considered as an endorsement of a particular power system concept.

Table 1
Reactor Fuel Parameters

	Near Term	Far Term	Goal
Fuel Pellet Density	96% TD*	96% TD	96% TD
Smear Density	89% TD	80% TD	80% TD
Maximum Burnup	6%	9%	12%
Cladding	PWC-11	W/Re	W/Re
Max. Fuel Temperature	1650 K	1700 K	1800 K
Max. Cladding Temperature	1400 K	1500 K	1600 K

Table 2
Payload Dose Limits

	Near Term	Far Term	Goal
Payload Neutron Dose Limit (n/cm^2)	1×10^{13}	5×10^{14}	1×10^{16}
Payload Gamma Dose Limit (R)	5×10^{5}	5×10^{6}	5×10^{7}

Table 3
Assumed Technology Improvements for Balance of System

	Near Term	Far Term	Goal
Heat Exchanger Mass	SP-100	3/4 x SP-100	1/2 x SP-100
Percent of Carnot Efficiency of Stirling+Linear Alternator	50%	60%	70%
Specific Mass of Stirling +Linear Alternator	6 kg/kWe	5.5 kg/kWe	5 kg/kWe
TE Figure of Merit	0.8×10^{-3} 1/K	1.4×10^{-3} 1/K	2.0×10^{-3} 1/K
Radiator Specific Mass	SP-100	3/4 x SP-100	1/2 x SP-100
Boom Mass	SP-100	3/4 x SP-100	1/2 x SP-100

* TD = Theoretical Density

The impact of advanced technology is illustrated in Figure 3 for a 5 MWe Stirling power conversion system assuming seven years of operation. Appreciable mass savings may be obtained if advancements in technology are assumed. Figure 4 illustrates the system mass impact of operational life for the various power conversion systems assuming 5 MWe power and near-term technology. Calculations were also performed assuming goal technology and cladding temperatures from 1400 K to 1600 K for each power system. The maximum mass savings resulting from high temperature opration was less than 15%.

OTHER CONSIDERATIONS

There are, of course, other important considerations besides mass; safety, for example, is a very important consideration. Operating conditions for the advanced technologies may be more severe than the conditions for the reference design and could raise additional safety issues. For example, high fuel and cladding temperatures may present safety problems for postulated loss-of-coolant accidents. On the other hand, some improvements, such as the cladding material, may offer safety advantages even with the more severe operating conditions.

Many reliability issues are closely related to safety issues. The more severe operating conditions for advanced designs might present some reliability problems. However, it has been assumed here that improvements in technology permit operation under more severe conditions without a reduction in reliability. Some advances may even improve reliability. For example, W/Re cladding does not depend on the integrity of a liner and is chemically compatible with both UN fuel and the Li coolant. Also, since W/Re has a body-centered-cubic lattice, there should be little cladding swelling due to neutron radiation damage.

CONCLUSIONS

We find no reason why the reference SP-100 reactor technology could not be used for power levels well into the MMWe range. Reactor and shield masses, for both the reference and advanced SP-100 technology, are comparable to the masses for proposed multimegawatt reactor concepts; in fact, we could not identify any essential differences between a reactor derived from SP-100 technology and any other pin-type liquid-metal cooled reactor specifically designed for high power operation. (We do not include in-core thermionics in our definition of pin-type reactors.) Although near-term power conversion technologies (Stirling, Brayton, and thermoelectric) could be used in the multimegawatt power range, the mass penalty is relatively large. The Rankine power conversion subsystem is expected to have the lowest mass and should be well suited to the multimegawatt power range; however, the Rankine concept is not considered to be near-term technology.

In addition to possible cladding and dimensional modifications for the SP-100 reactor, some modification of the auxiliary cooling system, control method (e.g., in-core control rods), thaw hardware, and other components may be necessary for high power systems.

ACKNOWLEDGEMENTS

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Figure 1
Reactor Mass vs. Power

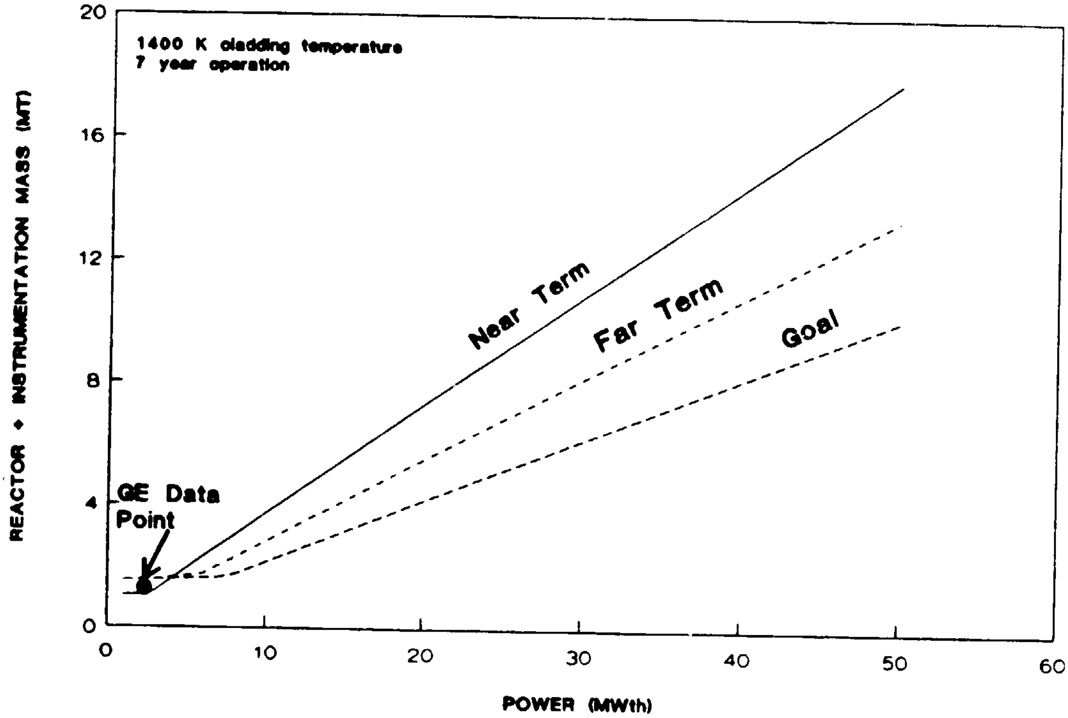
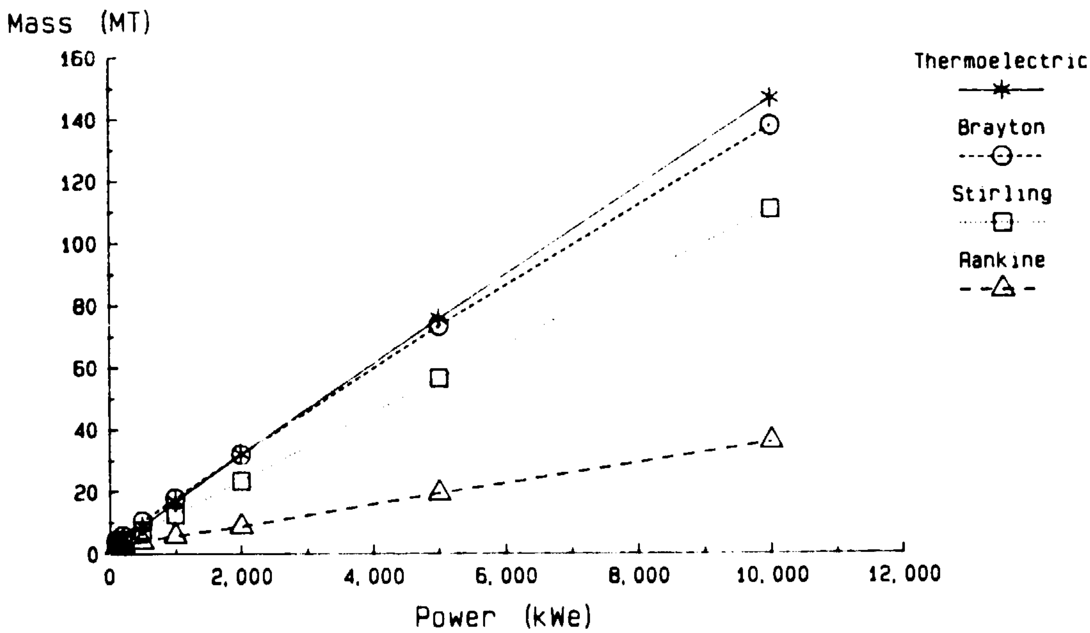
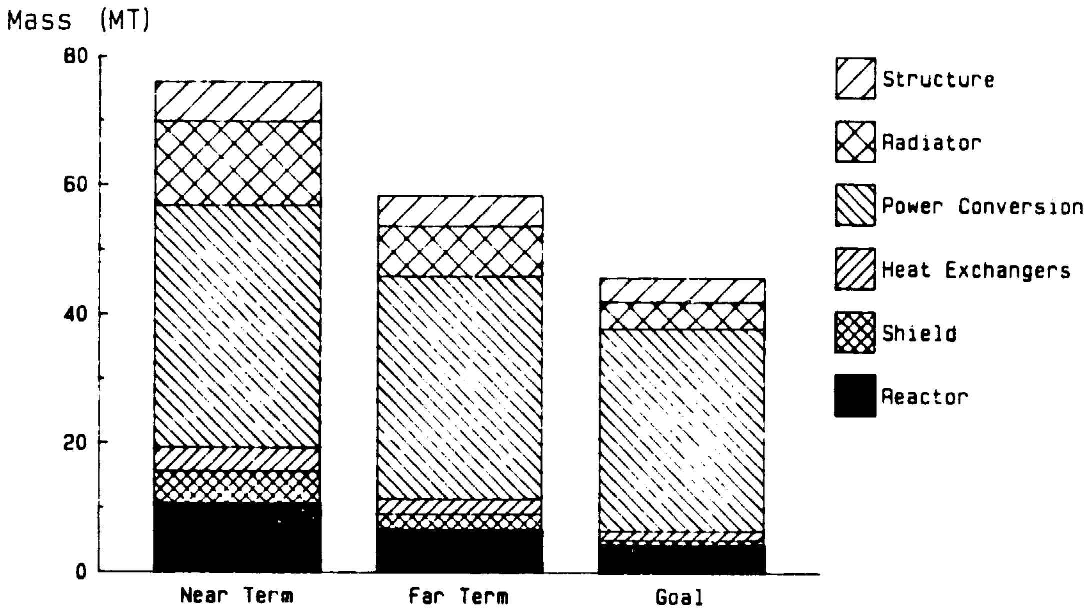


Figure 2
System Mass for a Range of Power Levels



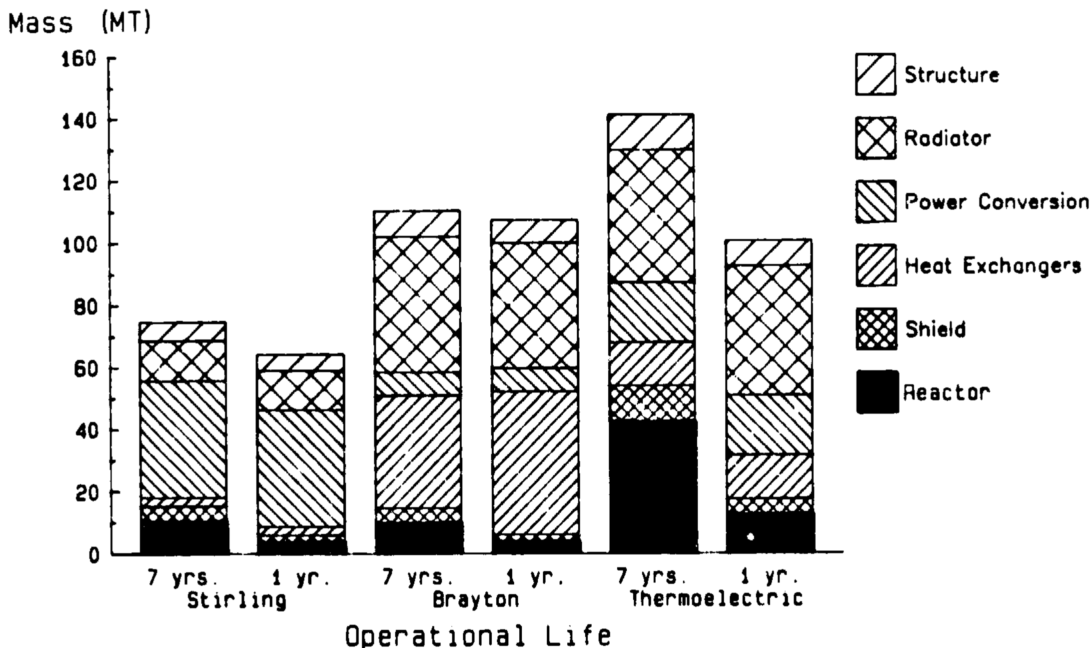
Far term technology
1500 K Max. Cladding Temperature
7 year life

Figure 3
Impact of Technology Improvements on Stirling Systems



5 MWe
1400 K Max. Cladding Temperature
7 year life

Figure 4
Effects of Operating Lifetime on Mass



Near Term Technology
1400 K Max. Cladding Temperature
5 MWe